# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2459

## SOME EFFECTS OF VARYING THE DAMPING IN PITCH AND ROLL ON THE FLYING QUALITIES OF A SMALL SINGLE-ROTOR HELICOPTER

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## SUMMARY

Flight-test measurements and pilots' opinions are presented of the longitudinal flying qualities and lateral control characteristics of a small single-rotor helicopter. In these tests the damping of the helicopter in pitch and roll was varied by means of a rate-sensitive automatic-control device from the amount present in the helicopter with the device inoperative to nearly three times that amount.

Longitudinal stability and control characteristics which were unsatisfactory with the device inoperative were improved by increasing the damping of the helicopter and were judged as satisfactory when the damping was approximately doubled by the device. The tests tended to confirm the proposed requirements of NACA TN 1983 that, for satisfactory stability, the curve for normal acceleration in a pull-and-hold maneuver should become concave downward within 2 seconds of the start of the maneuver.

The largest amount of damping tested resulted in correspondingly reduced rates of roll. Although noticeably low, these rates, however, seemed adequate to the pilots for normal flying.

## INTRODUCTION

During early flight research with a single-rotor helicopter at the Langley Aeronautical Laboratory, deficiencies in flying qualities were noted. These deficiencies were also experienced during familiarization flights with other helicopter types and are discussed qualitatively in reference 1.

Tentative requirements for satisfactory longitudinal stability were established in reference 2 primarily on the basis of tests in which maneuvering stability was varied in one helicopter by changes in angle-of-attack stability as effected by the addition of a horizontal tail (configurations A and B of reference 2). A check on the generality of the tentative requirements by varying the characteristics of a different helicopter by other means, however, was considered desirable. Tests were, therefore, conducted with a small helicopter having, as standard equipment, a gyroscopic stabilizing device that adds rotor damping in roll and pitch. By means of this device a variation of the damping of the helicopter over nearly a 3 to 1 range was possible and thus large changes in longitudinal characteristics were produced. The effects of variation of damping on the lateral controllability of the helicopter also could be determined. The results of these tests are reported herein.

## SYMBOLS

$\Delta b'$ lateral tilt of rotor resultant force vector resulting from rolling velocity, radians

$p$ rolling velocity, radians per second

$\Delta b'/p$ damping factor, or the lateral tilt of rotor resultant force vector per unit rolling velocity

$R$ rotor radius, feet

$r$ radial distance to blade element, feet

$x = \frac{r}{R}$

Subscript:

max maximum

## EQUIPMENT, INSTRUMENTATION, AND TESTS

### Test Aircraft

The test aircraft was a two-place helicopter having a single, two-blade main rotor mounted on a rocking hinge, a conventional tail rotor, and a gyroscopic stabilizing device beneath the main rotor. The diameter of the rotor was about 35 feet and the average gross weight of the helicopter for the tests was about 2050 pounds. A photograph of the test helicopter is shown as figure 1, and the principal dimensions and physical characteristics of the helicopter are listed in table I.

## Stabilizing Device

A close-up photograph of the rotor hub and stabilizing device is shown as figure 2. The device consists of a bar with weighted ends mounted on the rotor shaft at right angles to the blades on a pivot which allows the bar to seesaw while rotating, a mixing linkage which introduces into each of the blades a cyclic-pitch change proportional to the tilt of the bar from perpendicular to the shaft, and hydraulic restrainers which oppose the see-saw motion of the bar relative to the shaft. The forces from the restrainers cause the plane of rotation of the bar to precess toward the perpendicular to the shaft. When the helicopter is rolling or pitching, however, the inertia of the bar weights causes the plane of the bar to lag behind the shaft by a small angle, and the mixing linkage then introduces cyclic blade feathering in a direction to oppose the angular motion of the helicopter. Tilt in the resultant force vector introduced by the device thus increases the damping of the helicopter in roll and pitch. The pilot is not directly aware of the action of the stabilizing device because the stabilizing feathering control is applied through a mixing linkage and is independent of the position of the pilot's control.

The effectiveness of the device was varied during the tests by adjusting the hydraulic restrainers: Soft settings permitted the bar to lag behind the shaft by a relatively large angle and hence introduced a relatively large amount of feathering; whereas stiff settings allowed relatively small amounts of lag and small amounts of feathering. The helicopter was also flown with the bar locked to the shaft by diagonal braces and the bar weights removed. In this configuration the device was inoperative; that is, no damping could be introduced by it.

## Instrumentation

Instrumentation, consisting of standard NACA continuously recording instruments, was installed to record the following quantities: indicated airspeed, normal acceleration, stick, directional, and collective-pitch control positions, angular velocity about three axes, and longitudinal inclination.

The limited time available made it impracticable to install satisfactory instrumentation which would record the amount of cyclic feathering introduced by the stabilizer bar in flight. The amount of damping introduced was therefore determined from the effect of the stabilizing device on the rate of roll of the helicopter.

## Tests

Since preliminary tests indicated only minor changes in flying qualities due to center-of-gravity changes, all the data presented in this paper were obtained with a convenient loading which gave a center-of-gravity location of 1.5 to 1.8 inches forward of the rotor shaft at take-off. All recorded maneuvers were commenced with normal rated rotor speed (333 rpm) at a moderate altitude (1500 to 3000 ft).

Because of the complication of moments due to angle-of-attack changes, a direct measure of damping in pitch of the helicopter in flight could not be obtained. The damping was therefore determined from rolling maneuvers. Since reference 3 indicates that the damping of the rotor varies with flight condition, the rolling maneuvers were performed at the same flight conditions as the pull-ups. In order to insure that large lateral attitude changes and, consequently, sideslip did not occur before maximum rate of roll was reached, a maneuver was first tried wherein the control was displaced first in one direction, then immediately reversed and held displaced in the opposite direction until maximum rate of roll was reached. Maximum rolling velocity, however, was reached quickly and apparently before appreciable sideslip developed when the control was simply deflected abruptly from trim and held fixed.

Longitudinal characteristics were observed and measured during pull-up maneuvers and oscillations at several forward speeds with the stabilizer-bar restrainers at several settings throughout their range of adjustment and with the stabilizer bar locked. Pull-ups were performed by pulling abruptly rearward on the control stick and then holding the stick fixed in the out-of-trim position until maximum acceleration had been reached or excessive attitude made recovery necessary. The oscillations were initiated by a pull-and-return-to-trim motion of the stick or by leaning forward briefly with controls fixed. The latter method was the most convenient one since it eliminated the difficulty of returning the control exactly to trim. Because of the small size of the helicopter, a substantial disturbance could be initiated in this manner.

Although the pull-up characteristics of the helicopter varied with speed and power condition, the effect of varying the damping on the characteristics was similar at various forward flight speeds and amounts of power, and, for simplicity, the results presented herein are limited to a representative flight condition, that of level flight at 80 miles per hour.

## RESULTS AND DISCUSSION

### Determination of Damping

For the purpose of correlating the pilots' impressions with the changes in damping in pitch and roll, a measure of the damping of the helicopter had to be obtained, as was mentioned previously. It was preferable to measure the damping of the helicopter in roll rather than in pitch to eliminate complications produced by the angle-of-attack changes involved in pitching maneuvers in forward flight. The damping is assumed to be always substantially the same in roll as in pitch.

At the time of maximum rate of roll in the test maneuvers, the rolling moment produced by control displacement is equal to the damping moment in roll, provided sideslip effects are absent. Time histories of typical rolling maneuvers for determination of damping in level flight at 80 miles per hour are shown in figure 3. The peak rolling velocity per unit stick displacement was reduced as the stabilizer-bar restrainers were softened although the initial angular acceleration was little affected. As explained in reference 3, the amount of lateral feathering control used per unit rolling velocity is considered a direct measure of the damping in roll $\Delta b'/p$.

Unless the damping introduced by the stabilizer bar varies nearly linearly with angular velocity, a correlation of pilots' impressions with damping changes produced by varying the settings of the hydraulic restrainers of the bar would be difficult. Measurements of the maximum rate of roll at each of several control deflections for the case where the damping introduced by the bar was greatest are shown in figure 4. Since the rate of roll is a linear function of the control displacement the contribution of the bar must have been proportional to the rate of roll.

The results of the roll tests for the various configurations are tabulated as the damping-in-roll factor $\Delta b'/p$ in table II for the various amounts of helicopter damping tested. The relative damping of the helicopter with respect to the level-flight, bar-locked condition at 80 miles per hour is also tabulated. For the level-flight condition at 80 miles per hour the relative damping was varied by as large a factor as 2.72 by means of the stabilizer bar. The damping obtained from some autorotation runs is also shown in table II and illustrates the change in damping of the rotor with operating conditions (reference 3). With the stabilizer bar locked there was a 71-percent increase in damping of the helicopter in autorotation as compared to the level-flight condition at 80 miles per hour.

## Pull-Up Time Histories

Time histories of control deflection, pitching velocity, and normal acceleration in test pull-ups from level-flight trim at 80 miles per hour are shown in figure 5 for four amounts of helicopter damping.

Figure 5(a) is for the basic helicopter (bar-locked configuration). This configuration was considered unsatisfactory since the development of normal acceleration was of a divergent nature over a considerable period of time. The records show constant angular acceleration (pitching velocity increasing linearly with time) for the first $1\frac{1}{2}$ seconds of the maneuver; this constant angular acceleration indicates that the angle-of-attack instability was equal to the damping for this part of the maneuver. Normal acceleration following the initial jump developed at an increasingly rapid rate (curve of normal acceleration concave upward) for a period of approximately $2\frac{1}{2}$ seconds. The normal acceleration, however, soon afterwards reached a peak and fell off, probably because of the loss in speed. The prolonged development of acceleration caused a substantial load factor to be reached with only a very small displacement of the controls. When pull-ups were performed with large amounts of control at this trim speed with the bar locked, it was necessary to use recovery control before the curve of normal acceleration became concave downward to avoid excessive flight attitudes or load factors from developing.

Figure 5(b) shows a typical pull-up with the stabilizer-bar restrainers adjusted to produce a relative damping of the helicopter in roll of 1.60. The characteristics of the helicopter in pull-ups were considered to be marginal in this configuration. The records show that the pitching angular acceleration decreased slowly, the decrease starting immediately after fixing the controls and indicating that the net pitching moment acting on the helicopter was changing in a stable direction. The normal acceleration developed at an increasingly rapid rate for slightly over 2 seconds. The rate of increase in slope of the curve of normal acceleration, however, was not so rapid as in the pull-up shown in figure 5(a). The load factor per unit stick deflection seems to have been reduced.

Figure 5(c) shows a typical pull-up in which the relative damping of the helicopter in roll was 1.98. The helicopter was considered satisfactory in pull-ups with this setting at this speed because it did not indicate a prolonged tendency toward divergence. The records indicate a more rapid reduction in pitching angular acceleration immediately after fixing the controls than in figures 5(a) and 5(b) and a substantial reduction in the load factor obtained per unit stick deflection. The normal acceleration developed more rapidly because of the larger control displacement used but the curve became concave downward in less than 2 seconds.

Figure 5(d) shows a pull-up with the stabilizer restrainers softened to increase the relative damping of the helicopter to 2.48. The helicopter was considered to be more satisfactory with this setting than with the previous setting since it appeared to exhibit a more stable response to longitudinal control. The records indicated a more rapid reduction in the angular acceleration produced initially by the controls, a further reduction in the time for the curve of normal acceleration to become concave downward, and a further reduction in the sensitivity of the controls.

The softest damper setting obtainable resulted in a relative damping of the helicopter of 2.72, a change apparently small enough with respect to the previous setting that further improvement in the pull-ups was not apparent.

In all configurations the degree of pilot satisfaction with the longitudinal characteristics of the helicopter in pull-ups corresponded to the degree of satisfaction with the characteristics for normal flying.

## Time for Curve of Acceleration to Become Concave Downward in Pull-Ups

For comparison with the tentative requirement proposed in reference 2 for satisfactory longitudinal characteristics in forward flight that in pull-ups the curve of normal acceleration against time should become concave downward in 2 seconds, the times to become concave downward during the test pull-ups from level flight at 80 miles per hour were plotted against the values of the damping factor $\Delta b'/p$. The plot (fig. 6) is divided into satisfactory, unsatisfactory, and marginal regions depending upon the pilots' opinions of the longitudinal characteristics in pull-ups and in normal flight at this speed. The pilots' opinions of the test helicopter tend to confirm the proposed requirement of reference 2; that is, the dividing region between satisfactory and unsatisfactory characteristics coincided with a time of about 2 seconds for the curve of normal acceleration to become concave downward. Satisfactory characteristics at this speed were obtained in the test helicopter when its damping was increased to approximately double the amount present in the basic helicopter (stabilizer bar locked).

The vertical scatter of data points in figure 6, although due partly to the difficulty of determining the exact point of inflection in the accelerometer record, is also due to nonlinearities with load factor, the data points having been taken from pull-ups of varying degrees of severity. The time to become concave downward in pull-ups to large load-factor increments was observed to be somewhat shorter than in gentle pull-ups.

Brief pauses in development of acceleration in pull-ups following control displacement were found in the recorded time histories but were not noted by the pilots when the characteristics in pull-ups were otherwise satisfactory. This fact suggests that the anticipation requirement of reference 2 be modified to permit a transient pause in development of acceleration when it is associated directly with the initial jump in acceleration. Figures 5(c) and 5(d) illustrate the presence of such transient pauses in pull-ups which were considered satisfactory.

## Longitudinal Oscillations

Periods and damping of the long-period, stick-fixed motion of the helicopter are tabulated in table III for three amounts of damping of the helicopter. The added damping in pitch due to the stabilizing device overcame the tendency toward simple divergence in high-speed forward flight found in the helicopter with the bar locked but did not result in a damped oscillation until the damping in pitch was increased to approximetely the maximum tested. The presence of a long-period oscillation, even with some degree of negative damping, however, did not cause the pilots to consider the helicopter unsatisfactory in normal flight when the characteristics observed in pull-ups were considered satisfactory.

The time for the normal acceleration to reach a value differing by $\frac{1}{4}g$ from unity after a disturbance caused by pulling the stick back $\frac{1}{2}$ inch for 1/2 second was determined from the oscillation records to enable a comparison to be made between pilots' opinion and the proposed alternate requirement of reference 2 that this time should not be less than 10 seconds. With the bar locked this time was slightly less than 10 seconds and indicated that the alternate requirement was not quite satisfied in this configuration. With other settings the time was greater than 10 seconds and indicated compliance with this requirement. The time to reach $\frac{1}{4}g$ was, however, found to be fairly critically dependent on the amplitude of control motion when the pull-up characteristics were considered marginal or better.

## Lateral Control

Average maximum rates of roll for the helicopter were calculated by multiplying the average of available left and right control by the rate of roll per unit lateral control from table II. These results are tabulated in table IV, as are the resulting vertical velocities at the edge of the rotor disk $pR$.

The helicopter was considered by the pilots to possess adequate rate of roll for normal flying in all of the configurations tested, although, as can be seen in table IV, the rates of roll were very noticeably lowered with the soft restrainer settings. The maximum rate of roll of this helicopter with the bar locked is already somewhat lower than has been encountered in other helicopters of similar size.

The ease of precision control as represented by accurate hovering was not believed by the pilots to have been appreciably changed by the large variation in damping encountered and the corresponding variation in rate of roll for given stick displacement. A factor which made a definite conclusion in this regard a little uncertain, however, was the presence of transient stick forces out of phase with the direction of stick motion with the softer restrainer settings. With the stabilizer bar locked these transient forces were not present. A moderate increase in cyclic-control friction by adjustment of the friction device at the base of the stick could be used to mask these forces, although the increased friction in itself was not considered desirable.

The feathering introduced by the stabilizer bar was apparently not effective exactly opposite to the rolling or pitching velocity of the helicopter, because with the device in operation the helicopter tended to pitch during rolling maneuvers. This tendency to pitch during rolling increased as the restrainers were made softer and became very pronounced at large control deflections with the softest restrainer setting tested. This feature was considered undesirable, but it was not thought to affect controllability seriously in normal maneuvering of the helicopter nor to affect the pilots' impressions of the ease of accurate hovering.

One reason for the adequacy of control in maneuvers even with the highest damping is believed to be the fact that the initial angular acceleration in roll or pitch produced by the controls is unaffected by the stabilizer bar, a displacement of which occurs only with angular velocity. The response of the helicopter to atmospheric disturbances also is reduced as the damping is increased so that approximately a fixed percentage of available control is probably used in turbulent air regardless of the stabilizer-bar effectiveness.

## CONCLUSIONS

The results of flying-qualities tests on a small single-rotor helicopter in which damping in pitch and roll was varied over a considerable range indicate the following conclusions:

1. By increasing the damping in pitch to approximately twice the damping of the basic helicopter the longitudinal characteristics of the test helicopter could be varied from unsatisfactory to satisfactory.

2. The tests tended to confirm the tentative longitudinal flying-qualities requirement proposed in NACA TN 1983 that, for satisfactory longitudinal characteristics, evidence of stability must be present in the development of normal acceleration within 2 seconds following application of controls in a pull-and-hold maneuver.

3. The largest values of damping in roll obtained in the tests resulted in much lower rates of roll than are usually available in a helicopter of this size, but, although the rates were noticeably low, no control difficulties were experienced and the controllability was judged as adequate for normal flight.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., September 26, 1951

## REFERENCES

1. Reeder, John P., and Gustafson, F. B.: On the Flying Qualities of Helicopters. NACA TN 1799, 1949.

2. Gustafson, F. B., Amer, Kenneth B., Haig, C. R., and Reeder, J. P.: Longitudinal Flying Qualities of Several Single-Rotor Helicopters in Forward Flight. NACA TN 1983, 1949.

3. Amer, Kenneth B.: Theory of Helicopter Damping in Pitch or Roll and a Comparison with Flight Measurements. NACA TN 2136, 1950.

TABLE I

PRINCIPAL DIMENSIONS AND PHYSICAL CHARACTERISTICS

OF TEST HELICOPTER

| | |
|---|---|
| Gross weight (typical flight value), pounds | 2050 |
| Pitching moment of inertia, slug-feet$^2$ | 1360 |
| Rolling moment of inertia, slug-feet$^2$ | 370 |
| Yawing moment of inertia, slug-feet$^2$ | 1070 |
| Estimated height rotor hub above center of gravity, feet | 4.5 |
| Rotor diameter, feet | 35.13 |
| Number of blades | 2 |
| Radius at which blade starts, percent | 10.8 |
| Chord, feet | 1.184 - 0.351x |
| Solidity (area weighed proportional to $x^3$) | 0.0330 |
| Rotor angular velocity, radians per second | 34.9 |
| Rotational tip speed, feet per second | 613 |
| Flapping moment of inertia per blade including mass of hub, slug-feet$^2$ | 252 |
| Cyclic-pitch-control range with bar neutral: | |
| Longitudinal, degrees | 14.3 |
| Lateral, degrees | 10.8 |
| Range of bar tilt between static stops, degrees | 4.5 |
| Cyclic pitch per degree bar tilt, degrees | 0.88 |

TABLE II

DAMPING OBTAINED FROM ROLL TESTS

| Setting of stabilizer-bar restrainers | Damping-in-roll factor, $\Delta b'/p$ (radians/radian/sec rolling velocity) | | Relative damping of helicopter with respect to the bar-locked, level-flight condition at 80 miles per hour | |
|---|---|---|---|---|
| | Level flight at 80 miles per hour | Autorotation | Level flight at 80 miles per hour | Autorotation |
| 1 (Stabilizer bar locked) | 0.077 | 0.132 | 1.00 | 1.71 |
| 2 | .123 | ----- | 1.60 | ---- |
| 3 | .152 | .206 | 1.98 | 2.68 |
| 4 | .191 | ----- | 2.48 | ---- |
| 5 (Softest obtainable setting of stabilizer-bar restrainers) | .209 | ----- | 2.72 | ---- |

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TABLE III

PERIODS AND DAMPING OF LONGITUDINAL OSCILLATIONS

| Setting of stabilizer-bar restrainers | Speed, (mph) | Period, (sec) | Amplitude ratio per cycle (percent) | Time to halve or double amplitude (sec) |
|---|---|---|---|---|
| 1 (Bar locked) | 30 | 30 | 190 | 32.7 (double) |
| | 40 | 24 | 170 | 31.4 (double) |
| | 50 | 18 | 200 | 18.0 (double) |
| | 60 | [a]18 | [a]600 | [a]7.0 (double) |
| | 70 | --- | [a]500 | [a]4.7 (double) |
| | 80 | --- | [a]600 | [a]4.1 (double) |
| 3 | 35 | 40 | 190 | 43.6 (double) |
| | 65 | 39 | 280 | 26.6 (double) |
| | 80 | --- | [a]440 | [a]10.5 (double) |
| 5 (Softest obtainable setting of stabilizer-bar restrainers) | 30 | 28 | 83 | 10.6 (halve) |
| | 40 | 31 | 95 | Very long |
| | 50 | 41 | 59 | 53 (halve) |
| | 60 | 34 | 56 | 41 (halve) |
| | 70 | (b) | (b) | (b) |
| | 80 | (b) | (b) | (b) |

[a]Estimated on build-up in less than 1 cycle.

[b]Disturbances damped, but small random motions remained.

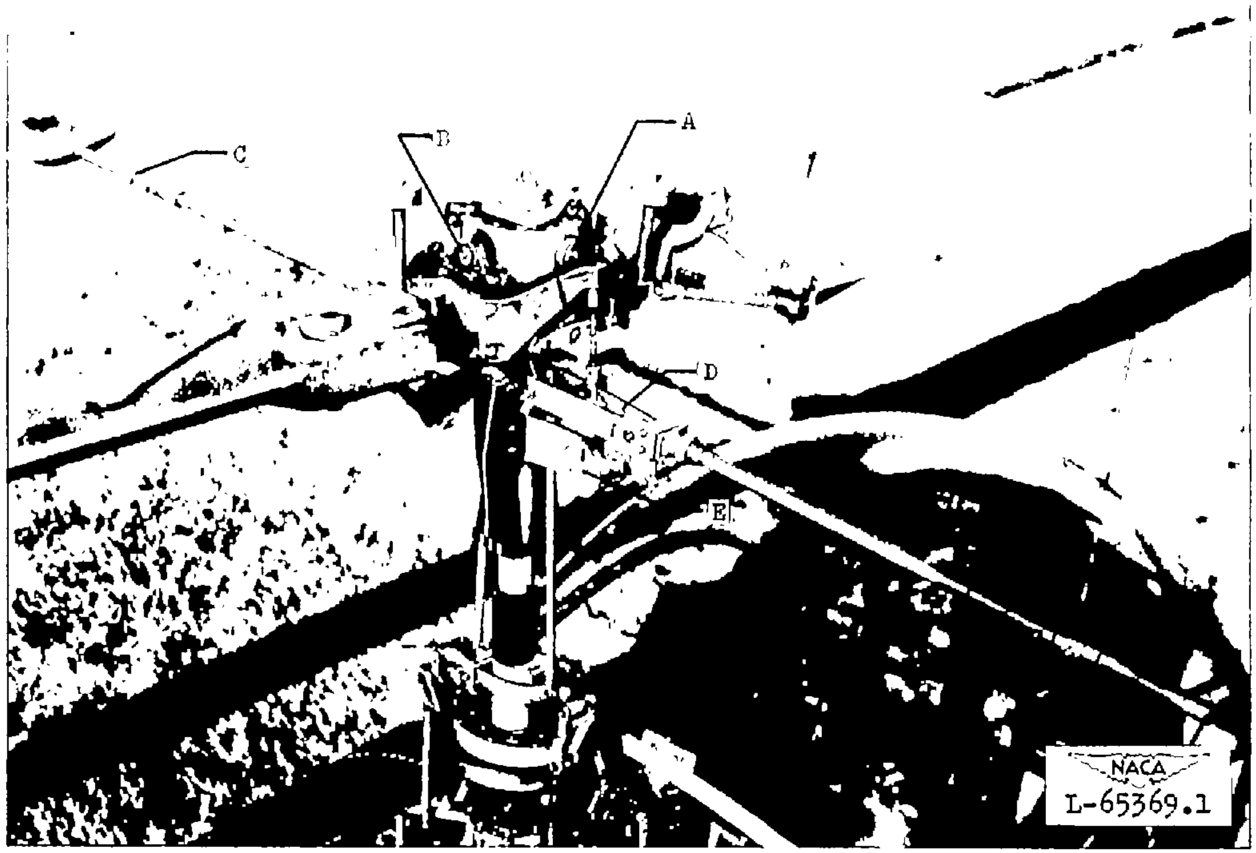
TABLE IV

AVERAGE MAXIMUM RATE OF ROLL FOR LEFT AND RIGHT CONTROL DEFLECTIONS

AND CORRESPONDING VERTICAL VELOCITIES AT THE ROTOR EDGE

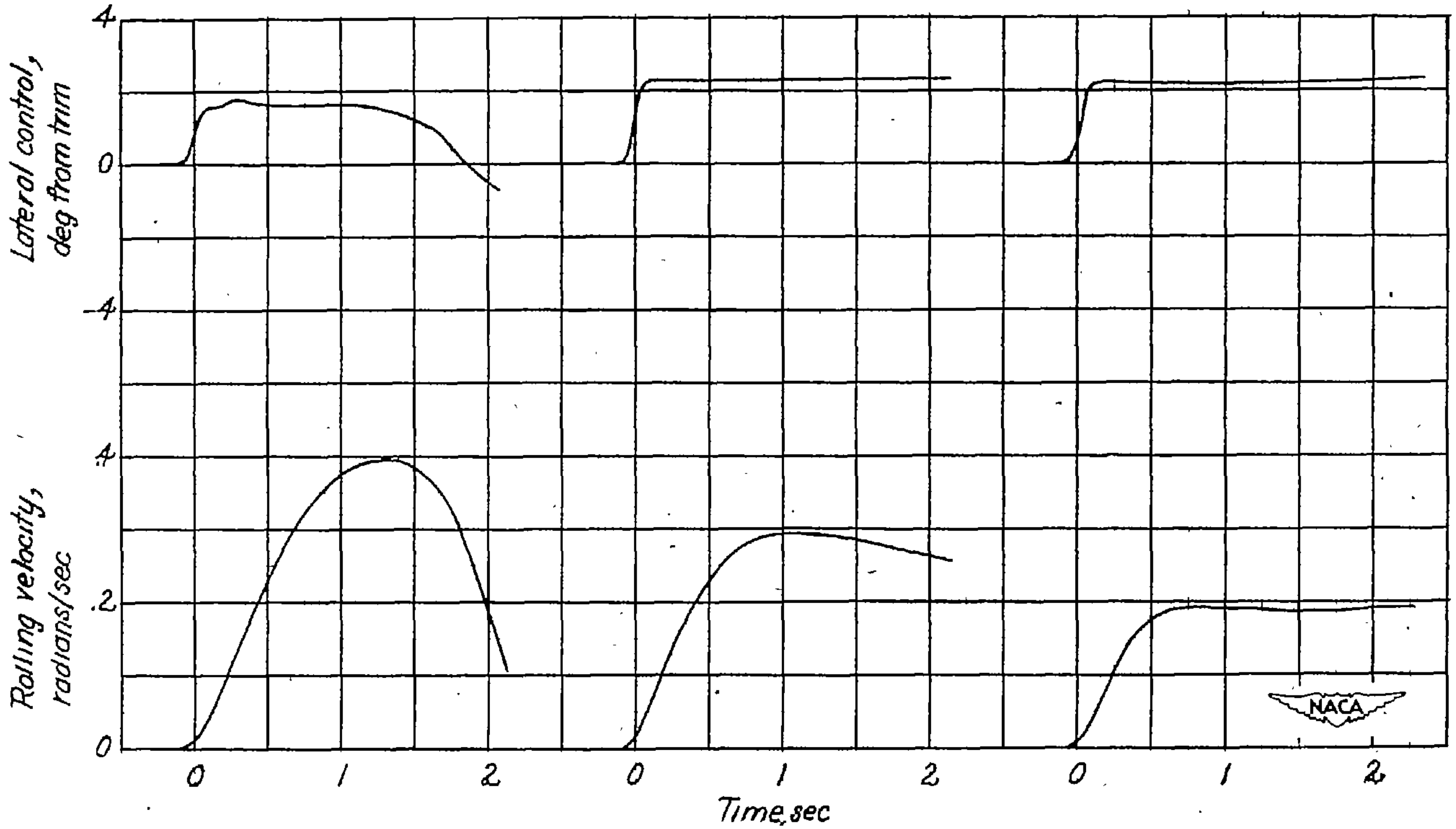
| Setting of stabilizer-bar restrainers | Level flight at 80 miles per hour | | Autorotation | |
|---|---|---|---|---|
| | $p_{max}$, (radians/sec) | $pR$, (ft/sec) | $p_{max}$, (radians/sec) | $pR$, (ft/sec) |
| 1 (Bar locked) | 1.22 | 21.4 | 0.72 | 12.6 |
| 2 | .77 | 13.5 | ---- | ---- |
| 3 | .62 | 10.9 | .46 | 8.1 |
| 4 | .49 | 8.6 | ---- | ---- |
| 5 (Softest obtainable setting of stabilizer-bar restrainers) | .45 | 7.9 | ---- | ---- |


Figure 1.- Photograph of test helicopter.




A Rocking hinge
B Feathering hinge
C Stabilizer bar
D Mixing linkage
E Hydraulic restrainers

Figure 2.- Photograph of stabilizing device on test helicopter.




(a) Basic helicopter (bar locked).

(b) Relative damping of helicopter, 1.60.

(c) Relative damping of helicopter, 2.48.

Figure 3.- Time histories of typical rolling maneuvers in level flight at 80 miles per hour.

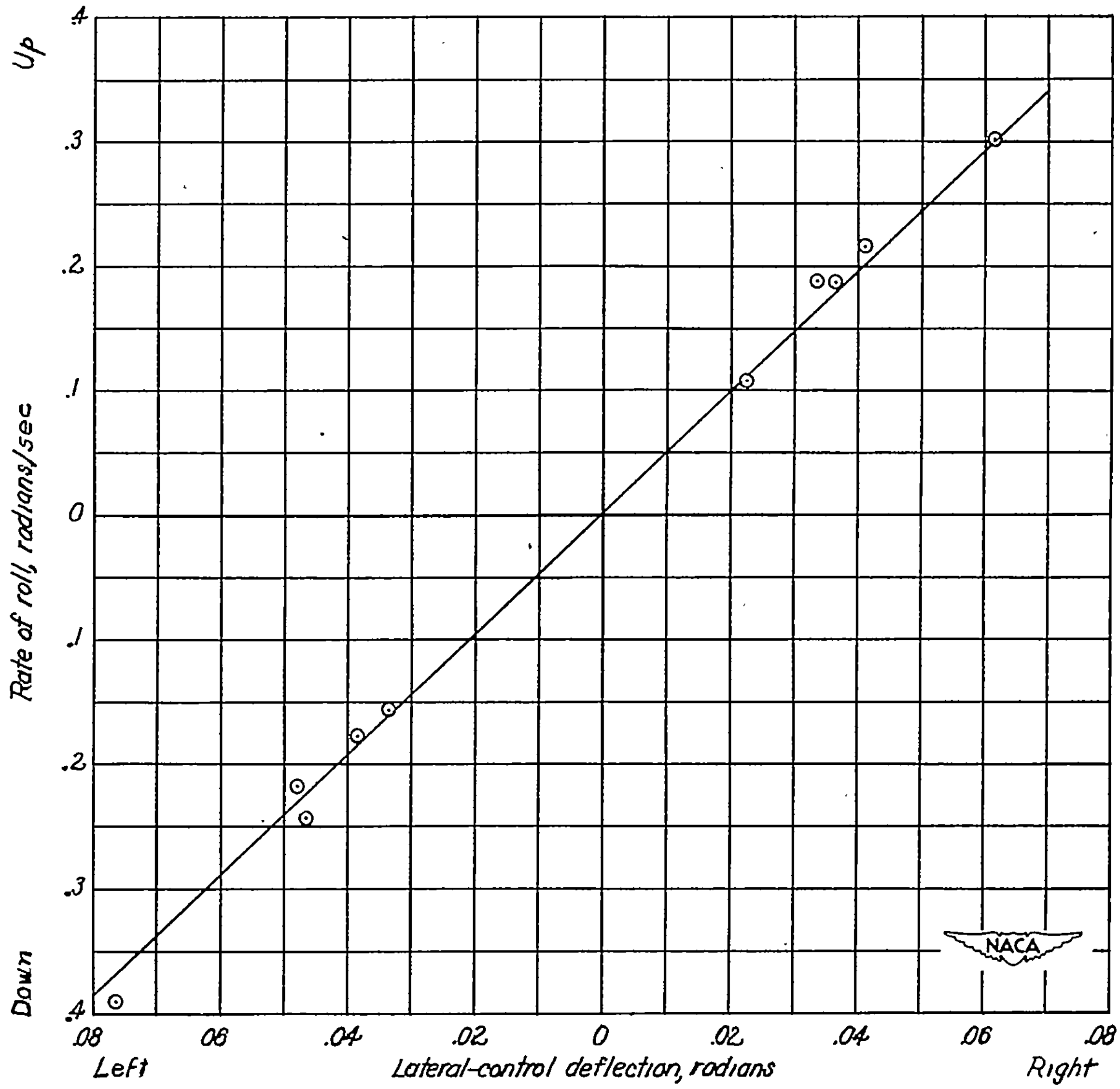
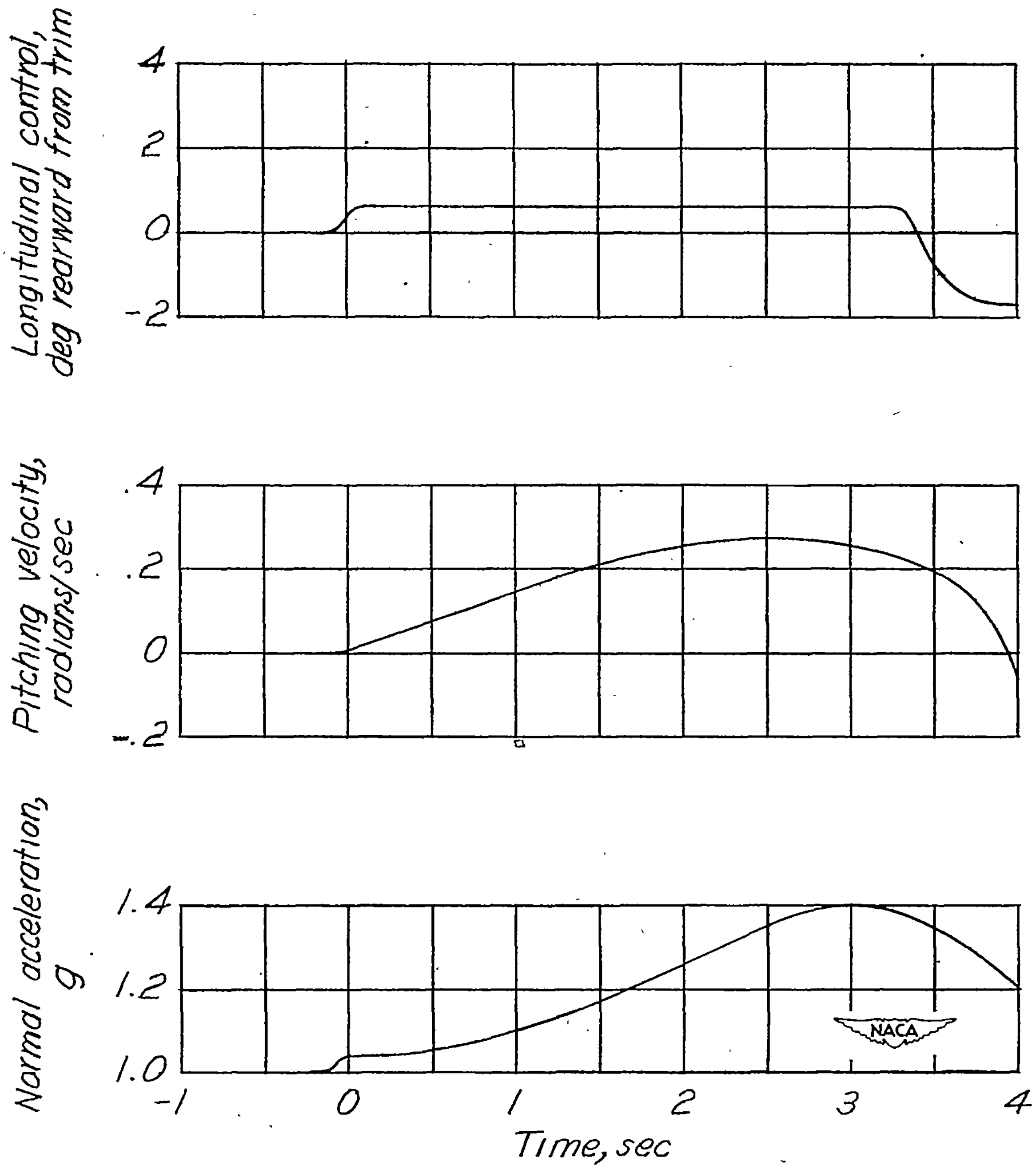
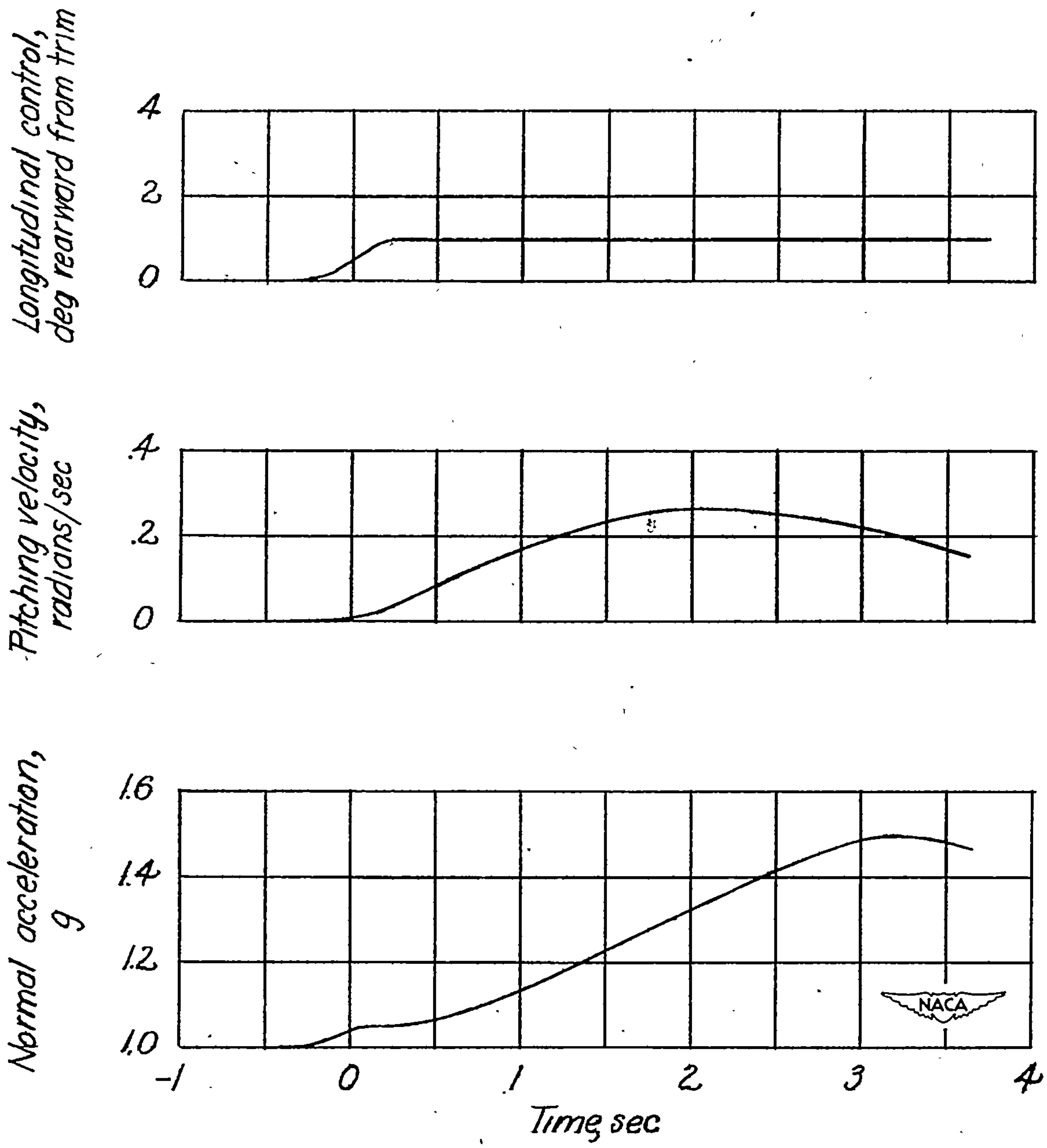



Figure 4.- Plot of maximum rate of roll against lateral-control deflection in level flight at 80 miles per hour. Relative damping of helicopter of 2.72 (softest obtainable setting of stabilizer-bar restrainers).



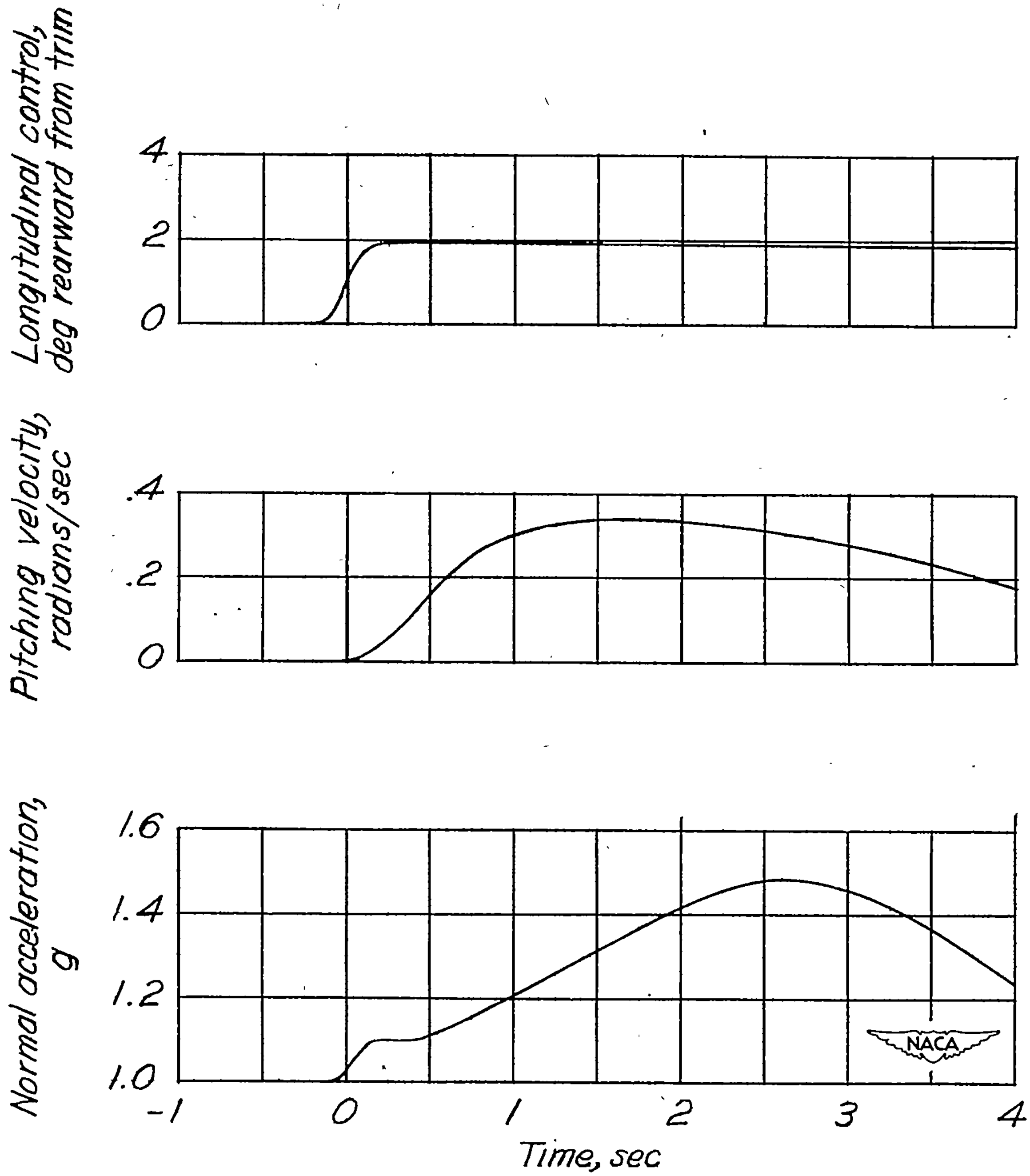

(a) Basic helicopter (bar locked).

Figure 5.- Time histories of pull-ups from level flight at 80 miles per hour.



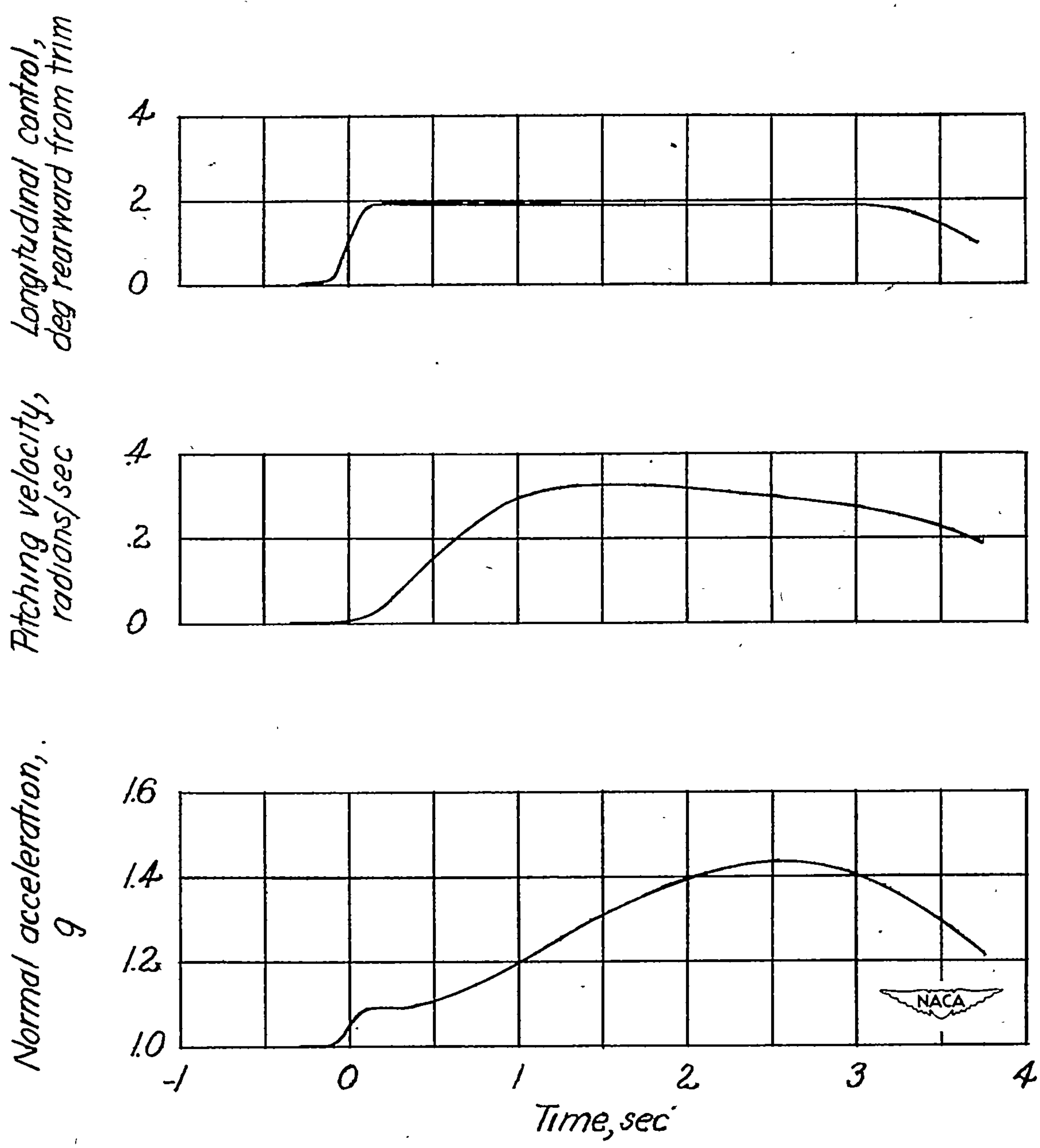

(b) Relative damping of helicopter, 1.60.

Figure 5.- Continued.




(c) Relative damping of helicopter, 1.98.

Figure 5.- Continued.




(d) Relative damping of helicopter, 2.48.

Figure 5.- Concluded.

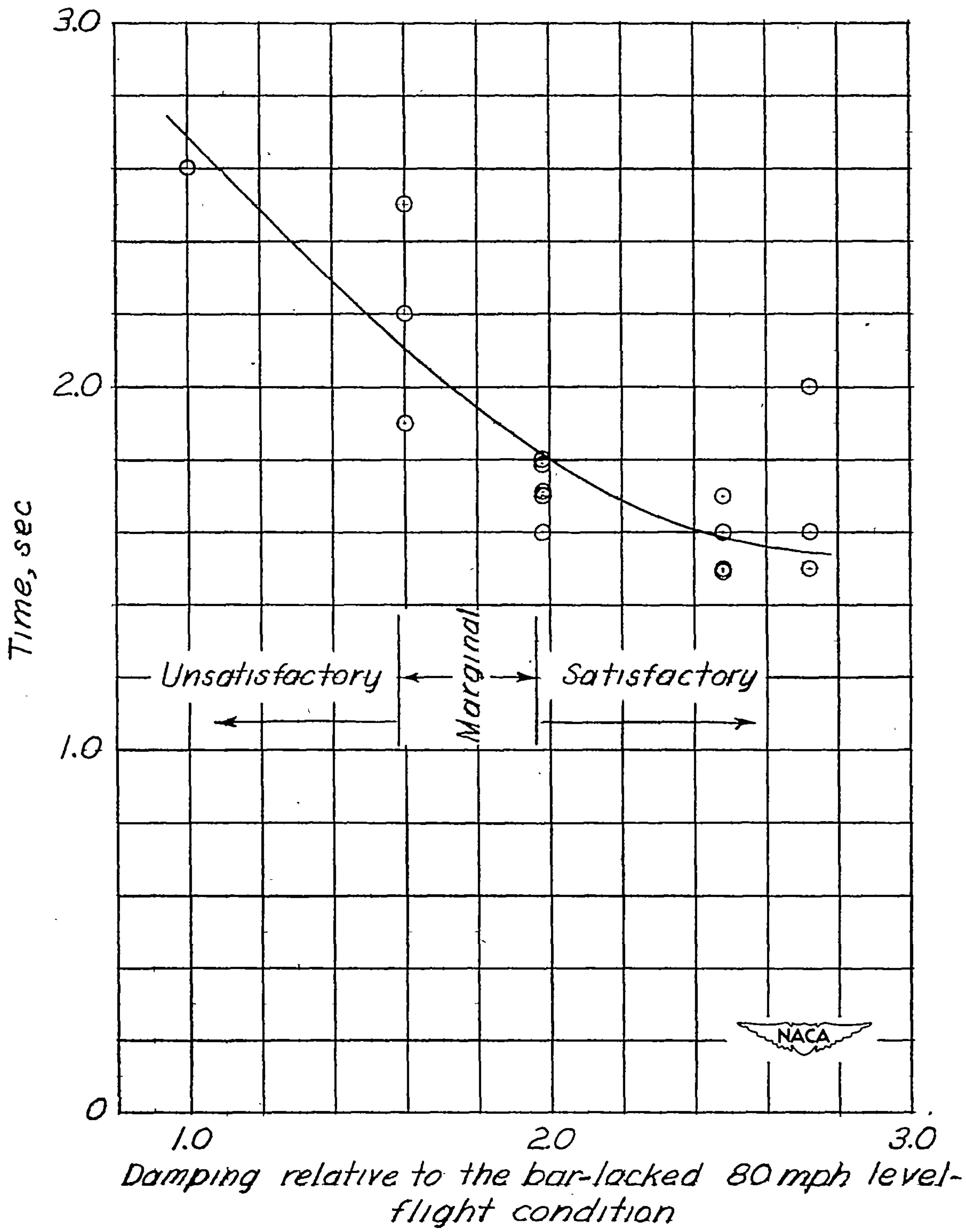



Figure 6.- Time from start of maneuver for curve of normal acceleration to become concave downward in pull-ups.

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